The Thesis Committee for Megan E. Micheletti
Certifies that this is the approved version of the following Thesis:

Objective Markers of Mother and Infant Behavior Predict Maternal Mental Health: Evidence from a Multimodal Sensing Paradigm

APPROVED BY
SUPERVISING COMMITTEE:

Kaya de Barbaro, Supervisor

A. Rebecca Neal-Beevers

Objective Markers of Mother and Infant Behavior Predict Maternal Mental Health: Evidence from a Multimodal Sensing Paradigm

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Megan E. Micheletti

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Abstract

Objective Markers of Mother and Infant Behavior Predict Maternal Mental Health: Evidence from a Multimodal Sensing Paradigm

Megan E. Micheletti, MA

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Supervisor: Kaya de Barbaro

Postpartum mood and anxiety disorders are among the most common mental health disorders experienced by women of reproductive age. Even more women encounter parenting stressors, fatigue, sleep disturbance, and mood disturbance or instability across the first year postpartum. Despite this, relatively little is known about the extent of and daily variability in mental health symptoms in postpartum women. In addition, little work has been conducted using objective methods to collect intensive, longitudinal, naturalistic data. N = 56 mother-infant dyads were recruited to participate in a week-long study in their homes using a multimodal sensing paradigm. The high-density sampling design was selected to capture potential variability in mental health symptoms. Multilevel methods were used to analyze both between- and within-participant effects of sleep, infant crying, and social support on maternal mental health. Between participants, lower mother and infant sleep quality predicted higher negative affect and depression levels; more infant crying predicted higher negative affect and anxiety levels; and lower social support predicted higher levels of negative affect, depression, and anxiety. Within participants, lower-than-average sleep quality and higher-than-average infant crying predicted higher levels of maternal negative affect. Social support emerged as an important predictor of maternal mental health and a potential mechanism by which to support mothers across the first year postpartum.

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Chapter 1: Introduction

The first year after a child is born is known to be a significant risk factor for the development of maternal mental health disorders (Witt et al., 2011). Approximately one in five women experience moderate to severe symptoms of depression and/or anxiety postpartum (Wisner et al., 2013) and a number of predictors have been identified, from biological and hormonal changes (Schiller et al., 2015; Yim et al., 2015) to parenting stress, partner relationship quality, and perceived social support (Yim et al., 2015). Although transient mental health symptoms often emerge up to two weeks after delivery during the "baby blues" (Wilkinson, 1999), it is estimated that up to 85% of mothers experience some type of mood disturbance in the postpartum period (Henshaw, 2003). For many mothers, parenting stressors, fatigue, sleep disturbance, and mood disturbance or instability can persist across the first year of an infant's life (Li et al., 2019). Despite the prevalence of these symptoms and the costs they take on maternal health and well-being (Britton, 2011; O'Hara & McCabe, 2013), limited work has systematically characterized the extent of and variability in maternal mental health symptoms in a community sample of postpartum women.

Postpartum mood and anxiety disorders are costly not only because of their effects on mothers, but also because of the adverse cascading consequences they have on infant cognitive, behavioral, and social-emotional development (Feldman et al., 2009; Goodman et al., 2011), well into adolescence and adulthood (Verbeek et al., 2012). The relationship between maternal mental health and infant development is bidirectional, however, such that mothers and infants influence one another through sequences of dynamic transactions over time (Murray et al., 2015; Sameroff, 1975). For example, an infant's own behavior (e.g., colic or excessive crying) is often associated with maternal depressive symptoms (Radesky et al., 2013) and even predictive of a postpartum depression diagnosis (Howell et al., 2005). Given this, it is important to understand not only the ways in which a mother might be constructing her own environment, including her infant's behavior, but also the ways in which her own environment is impacting her mental health. Three variables often considered meaningful aspects of a mother's environment in the postpartum period include sleep, infant crying, and social support.

Sleep

Broadly, individuals with sleep disturbances are at heightened risk for the development of mood disorders (Ford & Cooper-Patrick, 2001). Throughout at least the first two months following delivery, postpartum mothers experience fewer hours of sleep at night, more frequent nighttime awakenings, and reduced sleep efficiency relative to non-postpartum women (Swain et al., 1997). Poor sleep in the postpartum period has been shown to trigger depressive symptoms (Kurth et al., 2011) and has been linked to the development of postpartum depression, but not anxiety, across a number of systematic reviews (Bhati & Richards, 2015; Lawson et al., 2015). Furthermore, poor infant sleep has been identified as a family stressor and additional risk factor for maternal depression (Sadeh et al., 2010).

Infant crying

In addition to mother and infant sleep, infant crying is also a salient feature of a mother's postpartum environment (Young et al., 2012). Infant crying peaks at six weeks of age with nearly three hours of crying per day and decreases to less than one hour per day by three months (Wolke et al., 2017). Despite this developmental trend, large individual differences and within-infant daily fluctuations in crying duration have been identified (Kurth et al., 2011; St James-Roberts & Plewis, 1996). Broadly, mothers of infants with more prolonged periods of crying have been shown to exhibit higher levels of concurrent depression and anxiety (Petzoldt, 2018), caregiver frustration (Barr et al., 2014; Fujiwara et al., 2011), and emotional distress (Miller et al., 1993). Furthermore, mothers of infants with a difficult temperament, which includes high levels of irritability and crying, also exhibit higher levels of depressive symptoms (Britton, 2011).

Social support

Although the transition to motherhood ushers in many changes and potential stressors, social support has been identified as a predictor of smooth adjustment and adaptive parenting in the postpartum period (Goldstein et al., 1996). The definition of social support is largely dependent on the measure being used, but generally it captures the availability of and satisfaction with supportive interpersonal relationships. For postpartum women, social support has been shown to exert a protective function against the development of postpartum depression, particularly for mothers of infants with difficult temperaments (Cutrona & Troutman, 1986). Furthermore, poor social support networks and the absence of close relationships have been shown to predict levels of depressive symptoms in postpartum women (Eastwood et al., 2012) and low social support is a significant predictor of a mother's less positive attitudes towards her infant at one month postpartum (Crnic et al., 1983). Lowers levels of social support have also been linked to higher levels of both state and trait anxiety in postpartum mothers (Aktan, 2012).

Methodological limitations

Despite the number of studies linking sleep, infant crying, and social support to postpartum mental health—namely negative emotions, depression, and anxiety—this line of research is characterized by a number of methodological limitations. Specifically, most of this work was collected via parent report or from a structured protocol administered in a laboratory or home setting.

First, parent reports are not objective metrics of behavior. This is particularly troublesome for analyses using parent-reported sleep or infant crying as a predictor of maternal mental health. We know that mothers with a history of any psychopathology rate their children as having more internalizing and externalizing problems relative to teacher or therapist reports (Chilcoat & Breslau, 1997; Müller et al., 2011). While it is possible that mothers, teachers, and therapists are all capturing different samples of a child's behavior, this likely means that each observer is perceiving the child's behavior differently. This is important to consider before using parent reports of infant behavior as a predictor of maternal mental health. If mothers with a history of depression or anxiety are rating their infant as more temperamentally difficult, for example, then we cannot be sure whether it is the infant's difficult temperament that is influencing maternal mental health, or if a history of mental health problems is influencing a mother's perceptions of her infant's behavior.

Second, structured protocols in the laboratory, and even in the home, have the potential to limit ecological validity (Trull & Ebner-Priemer, 2014). The demands and constraints of laboratory settings can change and even alter the nature of observed phenomena (Lee et al., 2018) and a cross-sectional "snapshot" of behavior in the home might not be representative of the behavior as it naturally occurs day after day. Even longitudinal data sampled as much as every month or week has the potential to limit access to important variability in behavior (Mehl & Conner, 2011). In turn, this can limit insight into the role that day-to-day, or even within-day, fluctuations in any given behavior might influence a mother's mental health.

Current study

To understand the extent of and natural variability in mental health symptoms in postpartum women, we evaluated mothers and infants in their naturalistic environments using ecologically valid and objective measures. To do this, we deployed a multimodal sensing platform in the home to access symptoms of mental health as well as three theoretically-driven predictors of mental health: sleep, infant crying, and social support. By incorporating a high-density, repeated measures sampling design, we were equipped to capture variability in mental health symptoms and environmental predictors, as well as potential between- and within-subjects differences (Bolger & Laurenceau, 2013).

We decided to measure negative affect, depression, anxiety, and social support using ecological momentary assessment (EMA), or the repeated assessment of current symptoms or levels in the participant's natural environment (Shiffman et al., 2008). This approach was selected to reduce the effects of recall bias, which is especially common in assessments of emotional experience, and maximize ecological validity (Bolger & Laurenceau, 2013). We also used ambulatory, wearable devices to capture continuous assessments of mother and infant sleep as well as infant crying. This allowed us to capture objective measurements of behavior and reduce the impact of potential reporting biases. The key benefits of our study design were the opportunity to examine feelings and behaviors objectively in their natural spontaneous context and the potential to capture meaningful temporal processes between daily experiences and maternal mental health (de Barbaro, 2019).

Aims and Hypotheses

The first aim of the study was to deploy a multimodal sensing paradigm to measure naturalistic maternal mental health and mother and infant behaviors. We were interested in characterizing mothers' momentary negative affect, depression, anxiety, and social support as well as objective measures of mother and infant sleep and infant crying.

Our second aim was to test sleep, crying, and social support as predictors of maternal mental health. We were interested in both between- and within-person effects. We hypothesized that at the between-person level: mothers with poor sleep quality and mothers of infants with poor sleep quality would have higher levels of negative affect and depression, but not anxiety; mothers of infants with more and longer episodes of infant crying would having higher levels of negative affect, depression, and anxiety; and mothers with higher perceived social support would have lower levels of negative affect, depression, and anxiety. We also hypothesized that at the within-person level: decreases in mother and infant sleep quality would predict higher levels of negative affect and depression; increases in infant crying duration and frequency would predict higher levels of negative affect, depression, and anxiety; and increases in perceived social support would predict lower negative affect, depression, and anxiety.

Chapter 2: Methods

Participants

Mothers and their infants were recruited via convenience sampling from the greater Austin, Texas metropolitan area. Fliers were posted in local OB/GYN clinics, postpartum support groups, nonprofit family organizations, and the UT Austin Research Opportunities Calendar. Participants were also recruited from Facebook using the following advertisement parameters: women, ages 18-45, within 20 miles of Austin, TX, and New Parents (0-12 months). Exclusion criteria for the present study included infants older than 12 months of age, infants with congenital birth defects or a genetic condition (e.g., Down Syndrome), twins or other multiple birth infants, and a primary residence located over 20 miles from the UT Austin campus.

N = 59 participants enrolled in the study and n = 3 were excluded because of missing data, i.e., no survey responses. The final sample included n = 56 mother-infant dyads (Table 1). Infants were on average 3.8 months (SD=2.2), 56% female, and 43% Non-Hispanic white. Mothers were all female, approximately 31 years old (SD=6), and predominantly married (71%) and living in an English-speaking household (84%). 30% of mothers attended graduate school, 27% attended college, 25% had some college or trade school experience, and 18% had a high school degree or less. 50% of the sample earned over $75,000 in household income annually and 39% worked full-time, 20% worked part-time, and 41% were not employed.

Procedure

Study design and data collection were approved by UT Austin's Institutional Review Board (Protocol Number: 2017-06-0026).

Introductory session. Research assistants traveled to participants' homes to obtain written, informed consent and deliver wearable devices. Sessions were conducted in English or Spanish depending on the household's primary language. Following study consent and wearable device application, a series of experimenter-led tasks were video recorded to obtain baseline mother and infant physiological arousal, baseline infant movement, infant reactivity to novel stimuli, mother-infant free play, and daily routines in the home. Data from experimenter-led tasks were not included in the present study.

Home-recording session. Following the introductory session, mothers were instructed to wear the devices for an additional 72 hours over the course of the following week. Mothers were asked to record one 48-hour shift during which they planned to be with their child, typically the weekend, and two 12-hour shifts overnight. These recording windows were selected because they were largely feasible for mothers working full-time out of the home while still allowing ample continuous device wear-time. To maximize adherence to the recording paradigm, mothers selected their recording windows during their introductory session and throughout the week, research assistants sent text message reminders to put on the devices. At the end of the week, research assistants retrieved all wearable devices. Mothers were compensated $100 and infants received a small gift, like socks or a bib.

Wearable devices. Mothers were instructed how to use the devices during their introductory session. Objective sleep measures were obtained using the *Move4* ECG/activity sensor (movisens GmbH, Karlsruhe, Germany). Mother and infant each wore a sensor on their chest. Mothers wore the sensor on their chest under the left breast via hypoallergenic foam gel electrodes (VersaTrode A10005-3-7%, New York, United States). Infants wore the sensor in the center of their chest on the nipple line using hypoallergenic, gentle-adhesive, foam gel pediatric electrodes (TenderTrode A10001, New York, United States). Prior to application, the site was cleaned with a 70% isopropyl alcohol prep pad. The device was removed for bathing.

Objective measures of infant crying were obtained using Language Environment Analysis (LENA) technology (Xu et al., 2009). The LENA device is a small, child-safe recorder worn securely in a vest over the infant's clothing. The device can be worn for 24 hours at a time before losing charge. Thus, participants were given two LENA devices for their home recording session so that during the 48-hour recording, mothers could switch the recorder at 24 hours. The device records the infant's voice as well as other voices and sounds in the environment up to 10 feet away. During bathing or sleep, mothers removed the vest but kept it nearby to continue capturing ambulatory audio.

Ecological momentary assessments (EMAs). Mothers completed six signal-contingent, semi-random EMA surveys per day for the seven days they participated in the study. Signals were delivered to the mother's mobile phone via SMS text message (Hofmann & Patel, 2014). This signal prompted a survey response and contained a link to complete the two- to three-minute survey online via Qualtrics. Signals were considered semi-random because they were delivered at least two hours apart, but at otherwise random times between 05:00 – 07:49, 07:50 – 10:39, 10:40 – 13:29, 13:30 – 16:19, 16:20 – 19:09, and 19:10 – 22:00. Mothers received one survey per interval, totaling six per day. Short "in-the-moment" EMA surveys were administered repeatedly in lieu of a one-time measure of maternal mental health in order to improve ecological validity, minimize retrospective bias, and capture potential variability (Ebner-Priemer & Trull, 2009).

Measures

Mood, depression, and anxiety. Mothers reported momentary feelings of negative mood at each EMA survey as well as daily ratings of depression and anxiety once per day in the evening. Mood was measured using an adapted version of the Positive and Negative Affect Schedule, PANAS (Peeters et al., 2003; Watson et al., 1988). The negative affect scale was comprised of the following emotions: tense, anxious, guilty, irritable, and easily distracted. Every emotion was rated on a 1 – 7 scale and scores were averaged. Depression and anxiety levels were measured using the Patient Health Questionnaire-4 (Kroenke et al., 2009) and were scored on a 0 – 6 scale.

Mother and infant sleep. Maternal sleep was calculated using Movisens automated sleep detection algorithm (Barouni et al., 2020). Infant sleep was calculated from raw accelerometer data (Brønd et al., 2017) collected at 64 hz with sampling epochs of one minute using the Sadeh sleep algorithm (Sadeh et al., 1994). This algorithm was selected because it uses raw acceleration data rather than respiration rate like the Movisens algorithm. Infants have a higher respiration rate than adults, which could contribute to skewed infant sleep results using the Movisens algorithm (Galland et al., 2014).

Furthermore, the Movisens algorithm was not validated on infants, whereas the Sadeh algorithm has been previously validated in pediatric populations (Galland et al., 2012; Meltzer et al., 2012).

Inclusion criteria. First, to calculate nighttime sleep, the device had to be worn for at least 70% of the "nighttime" period from 17:00 – 9:59, which was selected to ensure capture of both first and last sleep episodes (Teti & Crosby, 2012). Next, sleep variables were calculated the same for mother and infant using definitions adopted from Teti et al. (2016). A sleep episode started with the first of at least 3 consecutive minutes of sleep (as determined by minute-by-minute sleep thresholds) and ended with the first five consecutive minutes of wake. Total sleep time was the total duration of all sleep episodes. Wake after sleep onset was calculated as the total duration of time in between sleep episodes in between bedtime (the start time of the first sleep episode after 17:00) and waketime (the end time of the last sleep episode that lasted at least 20 minutes before 10:00). Sleep fragmentation was defined as time spent awake between bedtime and waketime divided by total duration of all sleep episodes between bedtime and waketime. Sleep fragmentation is an overall metric of restless, non-recuperative sleep (Levine et al., 1987) where higher scores reflect a lower sleep quality.

Infant crying. First, we were interested in cry duration and frequency at different time intervals preceding EMA survey response. We were curious to examine the latency of the effect of infant crying on momentary mood and anxiety levels. For example, is maternal mood impacted any differently by within-person increases in infant crying over the past 10 minutes vs. 8 hours? As a result, crying in the following time intervals preceding EMA survey response were calculated: 10 minutes, 1 hour, 3 hours, and 8 hours.

Episodes of infant crying were first identified automatically using LENA software. Any nonverbal vocal expression of negative emotion, including fusses, whines, and whimpers in addition to cries, were automatically identified by LENA as crying (Fields-Olivieri & Cole, 2019). Hereafter, we refer to this collection of sounds as crying. LENA's non-vocalization category included episodes of crying, in addition to screams, laughs, and vegetative sounds like breathing and burping; overall, this category had an 84% agreement with human coders on vocalization vs. non-vocalization segment detection (Xu, Yapanel, & Gray, 2009). However, this analysis was done only on segments already identified by both LENA and human coders as having sounds produced by the child (Xu et al., 2009). This excludes segments that may have come from the child but were inaccurately labeled. In addition, the performance of the cry detection algorithm alone relative to human coders has not been previously published (Cristia, Bulgarelli, et al., 2020). To address this, we compared LENA cry detection and human codes for 40% of our participants.

Human transcription. Human coders annotated 24-hour recordings for *n* = 22 participants selected to represent the age distribution of our overall sample. A cry had to have a minimum duration of three seconds and fusses/whines/whimpers had no minimum duration (Gilkerson et al., 2017); all were combined and referred to as cries. Human coders achieved a Cohen's kappa of 0.77 for detecting cry and non-cry episodes, which represents a moderate to strong level of agreement (McHugh, 2012). Both frequency and duration of cries were compared. We found that LENA overestimated cry frequency by approximately

166 counts every 24 hours and underestimated cry duration by approximately 48 minutes every 24 hours. Given this sizeable discrepancy, we used the following data transformation to improve LENA-based cry estimates for all participants.

LENA data transformation. First, we estimated a linear regression model to predict the human-annotated cry durations and cry frequencies as a function of the LENA outputs, using all manually-annotated cry data. This was done for each time interval of interest, i.e., 10 minutes, 1 hour, 3 hours, and 8 hours. Then, we used the parameters of this regression to predict the human-annotated cry values for all LENA outputs at each time interval (Table 2). This resulted in LENA cry estimates more similar to the human-annotated values for each time frame. Although this approach to correcting LENA data is novel, recent research suggests that given LENA's tendency to underestimate child vocalizations, a correction factor might be applied to LENA data to compensate for this bias (Cristia, Lavechin, et al., 2020), which lends initial support for our method of transforming LENA cry data.

Inclusion criteria. Infants had to be wearing LENA for at least 70% of the interval for their data to be included in the analysis. If an infant had only been wearing the LENA for 5 hours, no data for crying in the past 8 hours were examined. However, if LENA was worn for more than 70% of the interval, cry values were evaluated. If wear-time was greater than 70% but less than 100%, crying values were normalized per minute and scaled up to the full interval. For example, if the infant had been wearing LENA for 7 hours, estimated cry values were normalized per minute and scaled up to the full 8 hours.

Social support. Mothers also reported their perceived social support once per day in the evening. Thinking about their day, mothers rated the extent to which the people available to them provided help doing things or provided emotional support when they needed it (1 = not at all, 2 = rarely, 3 = less than half the time, 4 = about half the time, 5 = more than half the time, 6 = almost always, 7 = always) as well as their satisfaction with the help/support provided to them today (1 = very dissatisfied, 2 = somewhat dissatisfied, 3 = neither satisfied nor dissatisfied, 4 = somewhat satisfied, 5 = very satisfied). Scores were averaged across all three responses resulting in a social support scale ranging from 1 – 6.33.

Data Analysis

All data analyses were conducted in R (3.5.0) and R Studio (Version 1.1.456). First, survey responses and objective sensor data were time-locked. For every EMA response, (a) cry frequency and duration in the preceding 10 minutes, 1 hour, 3 hours, and 8 hours were calculated and (b) sleep variables from the preceding night were obtained. Descriptive statistics on survey responses and sensor data were examined.

Next, we calculated intraclass correlation coefficients (ICCs) for each of our outcomes of interest – negative affect, depression, and anxiety. Single rater, one-way random effects ICCs (Bliese, 2000) were used to describe the percentage of total variance in negative affect, depression, and anxiety scores accounted for by between-subject differences (level 2 group membership).

Then, predictors were person-mean centered and within-person deviations from the mean were calculated (Bolger & Laurenceau, 2013; van de Pol & Wright, 2009). This allowed each variable to be split into between- and within-person components. In our first set of analyses, person-mean centered values for sleep, crying, and social support were tested as predictors of negative affect, depression, and anxiety. In this way, we could test associations between mean levels of a given behavior and mental health. For example, does a lower mean social support predict higher negative affect levels? Analyses were conducted across all EMA responses and participants. Predictors were tested in independent models and participant characteristics were included as covariates in the model if they were significantly associated with both the predictor and outcome.

Finally, given our nested data structure (multiple survey responses nested within individuals), our second set of analyses used predictive hierarchical multilevel modeling to separate between- and within- person effects. In this way, we could test at the participant-level whether recent deviations from an individual's own mean were predictive of their "in-the-moment" ratings of mental health. Within-person deviations in sleep, crying, and social support were tested as predictors of time-locked maternal negative affect, depression, and anxiety. Random effects were allowed for level 2 (participant) membership. Predictors were tested in independent models with the variable-specific, person-centered mean included as a predictor in the model. Participant characteristics were included as covariates if they were significantly associated with both the within-person predictor and the outcome of interest (Bliese, 2000) and models were based on completed cases only (missing values excluded).

Parameter estimates, or the unstandardized beta coefficients, were used to capture the magnitude of a single fixed effect on the dependent variable (Lorah, 2018). Effect sizes, or the standardized beta coefficients, were used to facilitate the comparison of magnitudes across different fixed effects after controlling for covariates and nesting (Snijders &

Berkhof, 2008). Effect sizes were calculated to compare parameter estimates amongst themselves as well as across different studies with similar populations (Lorah, 2018).

Chapter 3: Results

On average, mothers responded to 72% of survey signals (SD = 23, range = 16 – 100). Out of the recommended 72 hours of device wear-time, mothers wore their Movisens for a mean of 61 hours (SD = 24, range = 4 – 90). Infants wore their Movisens for a mean of 65 hours (SD = 24, range = 1 – 102) and LENA for 68 hours (SD = 19, range = 13 – 103).

Descriptive summaries of survey responses, sleep, and crying at the participant level are displayed in Table 3. Of note, mothers reported average depression and anxiety levels of 0.5 and 0.8, respectively, both of which are below the cutoff point of 3 used for identifying clinical concern on the PHQ-4 (Kroenke et al., 2009). No participants scored above threshold on depression and one participant had a mean anxiety level of 3. Three participants reported depression ≥ 3 on at least one occasion and eight participants reported anxiety ≥ 3 on at least one occasion.

Intraclass Correlation Coefficients

ICCs were calculated for negative affect, anxiety, and depression to obtain variance in scores between participants. Variance attributable to between-participant differences was 0.59 for negative affect, 0.59 for depression, and 0.53 for anxiety. This indicated that 41%, 41%, and 47% of the variability in negative affect, depression, and anxiety levels, respectively, were attributable to within-person variance. Figure 1 depicts level 1 negative affect, depression, and anxiety scores by level 2 participant grouping variable.

Between-person effects

Table 4 describes the results of simple regression analyses predicting negative affect, depression, and anxiety from person-mean centered predictors. Broadly, mothers of infants with higher mean levels of wake after sleep onset and higher crying (duration and frequency) in the past 1, 3, and 8 hours reported higher levels of negative affect. Mothers with higher depression scores had lower mean levels of nighttime sleep, higher mean levels of sleep fragmentation, as well as infants with a high mean wake after sleep onset. Mothers with high anxiety scores had infants with high mean levels of crying (duration and frequency) at 1 and 3 hours. Of note, low mean levels of social support predicted high levels of negative affect, depression, and anxiety.

Within-person effects

Each within-person model included two predictors, the within-person variation and the person-centered mean. Categorical variables were dummy coded. All participant characteristics were tested as potential confounds and included as a predictor in the model if significantly associated with the within-person predictor and dependent variable (Bliese, 2000).

Negative affect. No confounds were included in the predictive models for negative affect. Table 5 depicts results for the conditional models with negative affect as the dependent variable.

Sleep. Broadly, within-person decreases in maternal sleep quality predicted significantly higher levels of negative affect. At the participant-level, for every hour of maternal total sleep time more than the mean, mothers reported a decrease of 0.15 in negative affect ($p < .0001$); for every hour of maternal wake after sleep onset more than the mean, mothers reported a negative affect score that was 0.06 higher ($p = .02$); and when mothers had a sleep fragmentation ratio one unit higher than the mean, negative affect increased by 0.31 ($p = .03$). Comparing effect sizes, one standard deviation increase in mother TST, WASO, and SF was related to an expected -0.11, 0.05, and 0.05 standard deviation change in negative affect scores, respectively. This indicated that changes in total sleep time had the strongest effect, albeit relatively small, on maternal negative affect. We found no associations between within-person change in infant sleep quality and maternal negative affect.

Crying. Within-person increases in all tested crying variables predicted significantly higher levels of negative affect. An additional 10 minutes of crying more than the mean at each time interval predicted increases in negative affect: by 2.42 at 10 minutes ($p < .01$); 0.52 at 1 hour ($p = .01$); 0.28 at 3 hours ($p = .03$); and 0.14 at 8 hours ($p < .01$). Changes in cry frequency also predicted negative affect. With every 10 cry counts more than the mean, negative affect increased by 0.32 at 10 minutes ($p < .01$); 0.10 at 1 hour ($p < .001$); 0.01 at 3 hours ($p < .01$); and 0.02 at 8 hours ($p < .01$). Comparing effect sizes, within-person increases in cry frequency in the one hour preceding survey response had the strongest effect on negative affect ($\beta = .16$, $p <.001$).

Social support. Within-person increases in social support predicted significantly lower levels of negative affect ($B = -0.16$, $p = 0.02$, $\beta = -0.09$). For every one standard deviation increase in social support scores, negative affect was expected to decrease by 0.09 standard deviations.

Depression. Income was included as a covariate in the model testing change in mother's total sleep time as a predictor of depression. Results revealed that within-person changes in all mother and infant sleep variables did not predict levels of depression. Broadly, within-person changes in cry duration and frequency across all time intervals tested did not predict depression scores. However, within-person increases in social support predicted significantly lower levels of depression ($B = -0.22$, $p < .01$, $\beta = -0.20$).

Anxiety. No confounds were included in the predictive models for anxiety. No within-person changes in mother or infant sleep, or cry duration or frequency across all time intervals were predictive of anxiety. Within-person increases in social support significantly predicted lower levels of anxiety ($B = -0.12$, $p = 0.03$, $\beta = -0.09$). Comparing effect sizes, within-person increases in social support had the most positive impact on levels of depression ($\beta = -0.20$) followed by negative affect and anxiety ($\beta = -0.09$).

Post-hoc analyses including social support. Given that satisfaction with social support has been identified as a protective factor, we wanted to examine the extent to which perceived social support might explain the observed variance in maternal mental health scores beyond the variance explained by within-person changes in objective markers of sleep and crying. To address this, we included social support as a fixed effect in each of the independent models predicting negative affect from sleep and crying.

Results revealed that after accounting for the effects of social support, within-person decreases in maternal sleep quality (total sleep time, wake after sleep onset, and sleep fragmentation) and within-person increases in infant crying duration (at 10 minutes, 3 and 8 hours) and frequency (at 10 minutes, 1, 3, and 8 hours) no longer predicted higher levels of negative affect. An increase in cry duration in the previous hour was the only within-person predictor of negative affect that remained significant (*B* = 1.85, p = 0.045, β = 0.22) after including perceived social support in the model.

In summary, we added social support as a fixed effect in each of the independent models predicting negative affect from within-person changes in sleep and crying. After doing so, only within-person changes in cry duration in the previous hour remained a significant predictor of negative affect. For the remainder of the cry models, social support itself did not predict anxiety. However, in the sleep models, we found that social support predicted negative affect. Even after accounting for means and within-person deviations in maternal sleep quality, social support significantly predicted negative affect in the model for maternal total sleep time (*B* = -0.24, $p < .01$, β = -0.18), wake after sleep onset (*B* = -0.25, $p < .01$, β = -0.24), and sleep fragmentation (*B* = -0.25, $p < .01$, β = -0.05), such that higher levels of social support predicted lower negative affect scores. Broadly, this indicated that mother's ratings of perceived social support were a better indicator of her negative affect than any individual changes in her sleep quality the previous night.

Chapter 4: Discussion

The aims of this study were to use a multimodal sensing paradigm to measure maternal mental health and mother and infant behaviors in the home, and to examine sleep, crying, and social support as predictors of maternal mental health.

First, our data suggest it is feasible to use a multimodal sensing paradigm with mothers and infants to collect high-density, longitudinal, objective data. On average, mothers responded to 72% of surveys, wore their Movisens device for 88% of the intended time, and put the LENA and Movisens on their infant for 99% and 94% of the intended time, respectively. On average, the LENA device was worn for the longest time, followed by infant Movisens then mother Movisens. Of note, a number of dyads kept their sensors on for longer than the expected 72 hours and this data were included. It is possible that mothers were more likely to use the LENA device than Movisens because of the time required to apply electrodes as well as potential itching or discomfort at the application site. Using sensors that do not require electrodes and do not need to be removed for bathing would likely improve wear-time adherence.

Next, we found that in a community sample of postpartum women, individual differences in levels of negative affect, depression, and anxiety were observed. This is to say that even in a sample of women largely below clinical cutoffs on scales of depression and anxiety, there were still between-participant differences in mental health symptom levels. We also observed considerable within-person fluctuations in levels of negative affect, depression, and anxiety over the course of the week. As depicted in Figure 1, between-person effects were present, but a large proportion of the variance in scores was attributable to within-person fluctuations. This was a key feature of why we selected a high-density, longitudinal sampling design; had we not, we would not have been able to observe this natural variability in scores. Our next two analyses focused on the daily experiences of sleep, crying, and social support that might predict the observed levels of negative affect, depression, and anxiety.

First, between-person effects revealed associations between mean levels of sleep, crying, social support and momentary assessments of maternal mood and anxiety. Broadly, mothers of infants that cried often or for long bouts of time between the 1 and 8 hours preceding survey response reported high levels of negative affect and anxiety. This is generally consistent with the literature suggesting that excessive infant crying is associated with both depressive symptoms and anxiety (Petzoldt, 2018). In terms of sleep quality, we observed that mothers that spent more time awake after their first sleep episode had higher levels of negative affect. Higher levels of anxiety were observed in mothers that had higher sleep fragmentation, lower total nighttime sleep, and infants that spent more time awake after their first sleep episode. That so many sleep variables predicted anxiety was surprising given the extant literature's focus on sleep as a predictor of negative affect and depression, but not anxiety. However, recent work has proposed a model that relates infant sleep to maternal anxiety: Teti and Crosby (2012) found that elevated maternal worries about infant night waking lead mothers to seek out and spend more time with their infants at night, which in turn led to more infant night waking. This is to say that a mother's anxiety about her infant's sleep quality actually led to worse infant sleep quality. Although we did not test maternal anxiety as a predictor of infant sleep, we did find that both mother and infant sleep quality predicted maternal anxiety, which is largely consistent with this account of maternal anxiety and sleep (Teti & Crosby, 2012). Finally, mothers with higher mean levels of social support reported lower levels of negative affect, depression, and anxiety, which is consistent with existing work (Aktan, 2012; Cutrona & Troutman, 1986).

Second, given our repeated sampling design, we were able to calculate individuals' deviations from their own mean levels of sleep, crying, and social support and use such within-person fluctuations as a predictor of concurrent mental health. Most consistently, increases (i.e., scores higher than the individual's own mean) in social support predicted significantly lower levels of time-locked negative affect, depression, and anxiety. When a mother felt like she was supported better than usual over the course of the day, she was more likely to report fewer mental health symptoms that evening; which is consistent with the protective function that social support may provide.

We also found that when an infant cried more or for longer than was typical, mothers reported high levels of negative affect. Given the emotional distress and discomfort associated with excessive infant crying for mothers (Miller et al., 1993), it makes sense that higher-than-average infant crying at the individual level would also be associated with higher negative affect. While significant at all time intervals evaluated, we found that longer and more frequent crying in the 1 hour preceding survey responses had the strongest effect on negative affect. This might suggest that above-average crying in the past hour is recent enough to still be memorable, but not so recent (i.e., in the past 10 minutes) that the mother doesn't have as much time to process the increase.

Lastly, we found that decreases in mom's sleep quality, but not baby's sleep quality, predicted higher negative affect. For example, when a mother got less sleep than was typical, she reported a higher negative affect; but when an infant got less sleep than was typical, it didn't influence maternal mood or anxiety. Interestingly, mother's sleep variables and infant's sleep variables were not significantly correlated, pointing to the potential role that secondary caregivers might play in attending to the infant's nighttime needs (Feldman & Eidelman, 2007; McBride & Mills, 1993).

Of note, neither increases in cry duration and frequency nor decreases in mother or infant sleep quality predicted anxiety or depression levels. This could be because there were relatively fewer data points for anxiety and depression relative to negative affect (7 vs. 42 data points per person). After our primary analyses, we did test negative affect as a predictor of depression and anxiety and found that within-person increases in negative affect predicted higher levels of depression and anxiety. Given this, it is possible that the effects of sleep, crying, and social support influence anxiety and depression over the course of a longer timescale.

Finally, our post-hoc analyses revealed that social support buffered the effects of within-person increases in crying and decreases in maternal sleep quality on maternal negative affect. This is to say that a mother's evaluation of her social support over the course of the day explained more of the variance in negative affect than her infant's above or below average crying across the past 8 hours. In addition, social support was a better predictor of negative affect than fluctuations above or below average in sleep quality the previous night. Specifically, higher social support was predictive of lower negative affect, regardless of fluctuations in sleep quality the previous night. Again, these results point to the protective function of social support and suggest that social support might exert a particularly protective effect on days characterized by higher-than-average infant crying or on days following lower-than-average maternal sleep quality.

Limitations

The present study had several limitations. First, participants were obtained through convenience sampling, meaning the sample is likely not representative of the broader postpartum community. However, our participant characteristics were fairly diverse (Table 1), suggesting that we were able to recruit mothers that varied across a number of demographic variables.

Second, we limited our predictors to objective data that could be collected in real time. For example, we did not test history of stressful life experiences, traumatic birth, or prior depressive episodes as predictors of mental health, despite the research identifying such experiences as risk factors for the development of postpartum depression and anxiety (Field, 2018; O'Hara & McCabe, 2013). Although a number of risk factors have been identified across genetic, environmental, and social domains (Yim et al., 2015), we were particularly interested in the role that real time daily experiences play in the expression of symptoms. In this way, we decided to take a fine-grained approach to understanding how maternal mental health is influenced by a mother's daily environment in the home.

Third, despite the longitudinal nature of the study, it was only a week in the life of a mother and her baby, which limited our ability to make strong conclusions about causal influences. Furthermore, the present study investigated only sleep, crying, and social support as predictors of maternal health. Given that we know maternal mental health can influence each of these "predictors," future research is needed to examine cross-lagged effects over time and extract a more causal structure.

Conclusion

The present study fills a gap in the current literature by identifying the extent of and natural variability in mental health symptoms in a community sample of postpartum women. We successfully used a multimodal sensing paradigm to measure maternal mental health and mother and infant behaviors longitudinally, objectively, and at high density in the home. We also identified considerable within-person variability in levels of negative affect, depression, and anxiety.

Given our nested study design, we were also able to analyze between- and within-person effects on maternal mental health. Between participants, lower mother and infant sleep quality predicted higher negative affect and depression levels; more infant crying predicted higher negative affect and anxiety levels; and lower social support predicted higher levels of negative affect, depression, and anxiety. Within participants, lower-than-average sleep quality and higher-than-average infant crying predicted higher levels of maternal negative affect. Social support also emerged as an important predictor of maternal mental health and a potential mechanism by which to support mothers across the first year postpartum.

Appendix

Table 1

Participant characteristics

	n (%)	M (SD), Range
Infant		
Age, months		3.8 (2.2), 0.9 – 10.6
Gestational age, weeks		38.9 (1.8), 31 – 41
Female sex	31 (56%)	
Race/Ethnicity		
White, Hispanic	9 (16%)	
White, Non-Hispanic	24 (43%)	
Black	6 (11%)	
Hispanic	10 (18%)	
Multiracial	7 (12%)	
Mother		
Age, years		31(6), 18 - 43
Female sex	56 (100%)	
Education		
High school or less	10 (18%)	
Some college or trade school	14 (25%)	
College	15 (27%)	
Graduate School	17 (30%)	
Race/Ethnicity		
White, Hispanic	4 (7%)	
White, Non-Hispanic	30 (54%)	
Black	6 (11%)	
Hispanic	10 (18%)	
Asian	2 (3%)	
Multiracial	4 (7%)	
Employment		
Full-time	20 (36%)	
Part-time	11 (20%)	
Not employed out of the home	23 (41%)	
Full-time and a second job	2 (3%)	
Family Status		
Married	40 (71%)	
Divorced	1 (2%)	
Single Parent	5 (9%)	
Living with a partner without marriage	10 (18%)	

Table 1, cont.

	n (%)	M (SD), Range
Household Income		
Under $25k	8 (14%)	
$25k – 49k	9 (16%)	
$50k – 74k	11 (20%)	
$75k – 99k	10 (18%)	
Over $100k	18 (32%)	
Primary Household Language		
English	47 (84%)	
Spanish	9 (16%)	
Number of other children in the home		0.9 (1.2), 0 – 5

Table 2

Correlations between LENA and Human cry annotations

Time Preceding Survey Response	**Cry Frequency**		**Cry Duration (minutes)**	
	R	Regression Equation	R	Regression Equation
8 hours	0.74	y = 0.2983x + 38.117	0.73	y = 2.8488x + 10.743
3 hours	0.74	y = 1.6616x + 1.3552	0.75	y = 3.1006x + 3.7147
1 hour	0.65	y = 0.2778x + 2.552	0.72	y = 2.9304x + 0.6545
10 minutes	0.61	y = 0.2647x + 0.8869	0.68	y = 2.8268x + 0.2253

Note. The linear regression of y = human-annotated crying on x = LENA-annotated crying. Units are in hours.

Table 3

Descriptive statistics for survey responses and objective markers of sleep and crying

	n	M (SD)
EMA Survey		
Negative Affect	56	2.2 (0.9)
Depression	53	0.5 (0.6)
Anxiety	53	0.8 (0.7)
Social Support	53	4.9 (1.1)
Nighttime Sleep		
Mother TST, hrs	43	7.0 (1.4)
Infant TST, hrs	42	11.4 (1.9)
Mother WASO, hrs	43	1.7 (1.3)
Infant WASO, hrs	42	5.1 (1.8)
Mother SF	43	0.34 (0.30)
Infant SF	42	0.57 (0.28)
Crying		
8 hour duration, mins	45	13.0 (4.0)
8 hour frequency	45	71 (27)
3 hour duration, mins	45	6.2 (1.9)
3 hour frequency	45	95 (79)
1 hour duration, mins	44	2.7 (1.0)
1 hour frequency	44	12 (6)
10 minutes duration, mins	45	0.4 (0.2)
10 minutes frequency	45	2 (1)

Note. TST = total sleep time; WASO = wake after sleep onset; SF = sleep fragmentation.

Table 4

Simple regression analyses for negative affect, depression, and anxiety by mean-centered predictors

	Negative Affect			Depression			Anxiety		
Mean-centered predictor	***B***	***t* (df)**	***p***	***B***	***t* (df)**	***p***	***B***	***t* (df)**	***p***
Mother TST	0.06	2.76 (1419)	<0.01	-0.11	-3.64 (247)	**<0.001**	0.02	0.63 (247)	0.53
Infant TST	-0.04	-2.49 (1393)	0.01	-0.06	-2.49 (248)	0.01	-0.04	-1.16 (248)	0.25
Mother WASO	0.0002	0.49 (1419)	0.63	0.001	2.01 (247)	0.05	0.00008	0.11 (247)	0.92
Infant WASO	0.0008	3.25 (1393)	**<0.01**	0.001	3.13 (248)	**<0.01**	0.0008	1.50 (248)	0.14
Mother SF	0.25	2.59 (1419)	<0.01	0.47	3.13 (247)	**<0.01**	0.18	0.96 (247)	0.34
Infant SF	0.26	2.44 (1393)	0.01	0.35	2.13 (248)	0.03	0.14	0.69 (248)	0.49
10 min cry duration	0.11	0.58 (1494)	0.57	-0.16	-0.49 (262)	0.63	0.19	0.46 (262)	0.65
10 min cry frequency	0.01	0.26 (1494)	0.80	-0.02	-0.58 (262)	0.56	0.01	0.24 (262)	0.81
1 hr cry duration	0.25	9.09 (1467)	**<0.001**	0.11	2.65 (259)	<0.01	0.19	3.46 (259)	**<0.001**
1 hr cry frequency	0.03	6.58 (1494)	**<0.001**	0.006	0.72 (262)	0.47	0.03	3.07 (262)	**<0.01**
3 hr cry duration	0.08	5.62 (1494)	**<0.001**	0.004	0.18 (262)	0.86	0.08	2.99 (262)	**<0.01**
3 hr cry frequency	0.002	6.61 (1494)	**<0.001**	-0.0004	-0.66 (262)	0.51	0.002	3.37 (262)	**<0.001**
8 hr cry duration	0.02	2.95 (1494)	**<0.01**	0.0007	0.06 (262)	0.95	0.04	2.61 (262)	<0.01
8 hr cry frequency	0.004	3.85 (1494)	**<0.001**	0.002	1.29 (56)	0.20	0.004	1.73 (56)	0.09
Social Support	-0.16	-7.02 (1665)	**<0.001**	-0.19	-5.83 (293)	**<0.001**	-0.18	-4.28 (293)	**<0.001**

Note. TST = total sleep time (hours); WASO = wake after sleep onset (hours); SF = sleep fragmentation. Cry duration in minutes. *P*-values were corrected for multiple testing using Bonferroni correction. Values that remained significant following correction are in bold.

Table 5

Linear mixed models predicting negative affect from within-person variations in sleep, crying, and social support

Observed effects	Estimate	*CI*	Test (*df*)	*p*	Effect Size (β)[a]
Nighttime Sleep[b]					
Mother TST	-0.15***	-0.21, -0.09	t = -4.73 (630.49)	<.0001	-0.11
Infant TST	0.01	-0.03, 0.05	t = 0.49 (520.43)	.62	0.01
Mother WASO	0.06*	0.01, 0.11	t = 2.27 (630.49)	.02	0.05
Infant WASO	0.03	-0.02. 0.09	t = 1.28 (520.43)	.20	0.03
Mother SF	0.31*	0.03, 0.60	t = 2.18 (630.49)	.03	0.05
Infant SF	0.05	-0.20, 0.30	t = 0.39 (520.43)	.70	0.01
Crying[c]					
10 minutes duration	2.42**	0.84, 4.00	t = 3.01 (486.58)	<.01	0.08
10 minutes frequency	0.32**	0.12, 0.52	t = 3.16 (492.60)	<.01	0.08
1 hour duration	0.52*	0.11, 0.92	t = 2.50 (271.45)	.01	0.09
1 hour frequency	0.10***	0.05, 0.14	t = 4.28 (469.50)	<.0001	0.16
3 hour duration	0.28*	0.04, 0.52	t = 2.26 (331.31)	.03	0.10
3 hour frequency	0.01**	0.00, 0.01	t = 3.26 (434.50)	<.01	0.07
8 hour duration	0.14***	0.04, 0.23	t = 2.89 (425.50)	<.001	0.06
8 hour frequency	0.02*	0.00, 0.03	t = 2.32 (425.30)	.02	0.07
Social Support	-0.16*	-0.28, -0.03	t = -2.42 (228.58)	.02	-0.09

Note. Nighttime sleep: TST = total sleep time; WASO = wake after sleep onset; SF = sleep fragmentation. Significance thresholds: * p < .05, ** p <.01, *** p <.001. CI = 95% confidence interval.

[a] β is the standardized beta coefficient

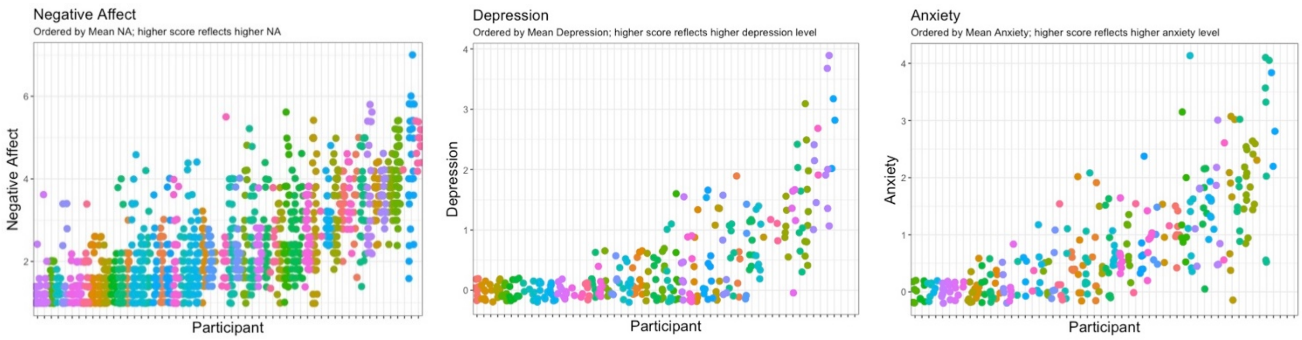
[b] Sleep TST and WASO estimates (unstandardized coefficients) are presented in 1 hour time blocks. E.g., with every hour increase of mother TST over the mean, negative affect decreases by 0.15

[c] Cry duration and frequency estimates are presented in 10 minute time blocks and 10 count frequency blocks. E.g., with every 10 minute increase of crying duration over the mean in a 10 minute time interval, negative affect increases by 2.42; and with every 10 minute increase in crying duration over the mean in an 8 hour time interval, negative affect increases by 0.14

Figure 1

Within-person variability in maternal mental health scores

A. B. C.



Within-person variability in (A) negative affect, 41%; (B) depression, 41%; and (C) anxiety, 47%. Each column reflects one participant. Scores are jittered and participants are ordered by mean level to illustrate variability.

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